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Optimum Design and Analyze Performance Parameters of Ice Plant Test Rig using R32 Refrigerant

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Abstract: *Ice plant systems have evolved significantly since the early development of mechanical refrigeration in the 19th century. Initially used for commercial ice production, these systems have been adapted over time for academic and research applications. The Ice Plant Test Rig, in particular, serves as an experimental platform to understand the practical workings of the vapor compression refrigeration cycle. It allows students and researchers to study key thermodynamic principles, component performance, and the behavior of refrigerants under varying thermal loads. Modern test rigs have incorporated advanced components and environmentally friendly refrigerants to align with current energy and sustainability standards. Various studies have investigated the performance of ice plant systems using different refrigerants and design configurations. Traditional refrigerants like R22 and R134a have been widely studied but are being phased out due to their high global warming potential. Recent research has focused on alternative refrigerants such as R32, known for its low GWP, high efficiency, and favorable thermodynamic characteristics. Shell-and-tube evaporators and air-cooled condensers have also been highlighted in the literature for their effectiveness in heat exchange and system simplicity. These findings provided a foundation for the current project, influencing the choice of components and refrigerant in the test rig design.*

This project involved the design, fabrication, and performance analysis of an Ice Plant Test Rig utilizing R32 refrigerant, targeting improved thermal efficiency and reduced environmental impact. The system comprised a hermetically sealed compressor, air-cooled condenser, capillary tube, and a shell-and-tube evaporator immersed in brine. It was designed for a cooling capacity of 0.25 TR, capable of managing a total heat load of about 390 W. Experimental evaluations included monitoring temperature profiles and calculating the Coefficient of Performance (COP). Results indicated that the system operated effectively within design parameters, with experimental COP values closely matching theoretical expectations. This confirms that the setup is efficient, cost-effective, and suitable for both small-scale ice production and educational use.

Keywords: Coefficient of Performance, cooling effect, work done, R-32 refrigerant, Global warming potential, Ton of Refrigeration, efficiency

I. INTRODUCTION

The Ice Plant Test Rig using R32 refrigerant operates on the basic principle of the vapor compression refrigeration cycle. In this system, R32 refrigerant is used as the working fluid due to its high energy efficiency and lower global warming potential. The cycle begins with the refrigerant in vapor form entering the compressor, where it is compressed to a high pressure and temperature. This high-pressure vapor then flows into the condenser, where it releases heat to the surroundings and condenses into a high-pressure liquid. The liquid refrigerant then passes through an expansion valve, where its pressure and temperature drop significantly, converting it into a low-pressure, low-temperature mixture of liquid and vapor. This cold mixture then enters the evaporator, which is in contact with

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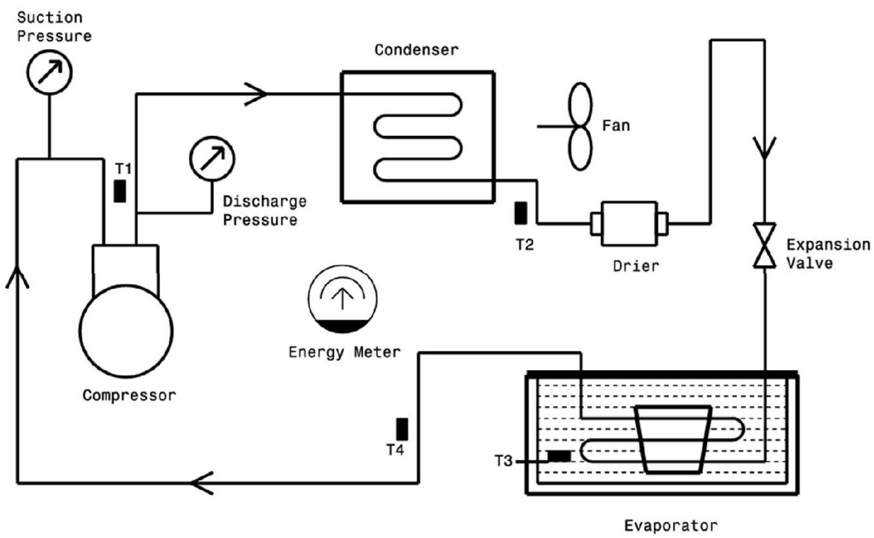
water-filled containers. In the evaporator, the refrigerant absorbs heat from the water, causing the water to freeze into ice. As the refrigerant absorbs this heat, it evaporates back into vapor form and returns to the compressor, repeating the cycle. Throughout this process, R32 plays a crucial role in efficiently transferring heat from the water to the external environment, enabling continuous ice production in the test rig setup.

Schematic Diagram of Ice Plant Setup



The major components used in the ice plant are described in the subsequent sections:

Compressor

The compressor may be viewed as the central component of the refrigeration cycle. It compresses the low-pressure refrigerant vapor drawn from the evaporator to high-pressure, high-temperature vapor. This process not only raises the pressure of the refrigerant but also its temperature, so it is well-suited for rejection of heat in the condenser. Depending upon the plant capacity and application, a range of compressors such as reciprocating, scroll, or rotary compressors can be used. Reciprocating compressors are common in small ice plants due to the fact that they are simple and efficient.

Condenser

The condenser is employed to drain the heat transferred by the refrigerant. When the high-pressure, high-temperature vapor from the compressor is pumped into the condenser, it releases its heat to the surrounding medium—air or water— thus condensing to a high-pressure liquid. Air-cooled condensers are utilized in areas with sufficient airflow and low humidity, whereas water-cooled condensers are used where water is readily available in large quantities. The condenser employed plays a significant role in the overall efficiency of the system.

Filter-Drier and Receiver

Liquid receiver is an auxiliary assembly used for liquid refrigerant storage after passing through the condenser. It allows refrigerant charge oscillations to be regulated and offers a stable supply to the expansion valve. In cases where purity of the refrigerant matters most, a filter-drier is also used to remove moisture, acid, and other impurities that could potentially damage system components or degrade performance over the long term

Expansion Valve or Capillary Tube

The expansion device also helps to reduce the pressure and temperature of the liquid refrigerant before it enters the evaporator. This reduction in pressure allows the refrigerant to evaporate at a lower temperature, which is essential for the absorption of heat. Thermostatic Expansion Valves (TEVs) are used in commercial systems most often since they are able to modulate flow according to load conditions, while capillary tubes are used in simpler systems since they are cheap and easy to operate.

Evaporator

The evaporator is the component where actual refrigeration takes place. The low-pressure refrigerant absorbs heat from the surroundings (in this case, the water or brine in the ice cans), causing it to evaporate. This heat extraction results in the freezing of water into ice. Depending on the system design, the evaporator may either be a direct expansion coil in contact with the water or an indirect system where it cools a brine solution that circulates around the ice cans. Proper evaporator design is critical to ensure efficient and uniform ice formation.

Brine Tank (Applicable in Indirect Cooling Systems)

In many traditional ice plants, an indirect cooling method is used where the evaporator cools a brine solution (typically a mix of water and salt). This chilled brine is then circulated around the submerged ice cans containing fresh water. The brine remains in liquid state even at sub-zero temperatures, ensuring consistent and controlled heat extraction. The use of brine also prevents the freezing of coils and enhances system safety and durability.

Brine Agitator and Circulation Pump

To ensure uniform temperature distribution within the brine tank and avoid stratification, an agitator and pump are employed. The agitator keeps the brine in constant motion, enhancing the heat transfer between the refrigerant and ice cans. This uniformity helps in achieving consistent freezing rates and prevents the formation of partial or uneven ice blocks.

Ice Cans or Molds

Ice cans are specially designed metal containers filled with clean water and submerged in the brine tank. As the cold brine absorbs heat from the water in these cans, it gradually freezes into solid ice blocks. The design of the cans—including their material, wall thickness, and size—plays an important role in determining the freezing time and quality of the ice. Galvanized steel or aluminum cans are commonly used for their corrosion resistance and thermal conductivity. 9. Defrosting or Ice Harvesting System Once the ice blocks are completely formed, they need to be removed from the cans. A defrosting mechanism is used to loosen the ice by melting a thin outer layer. This can be done using hot gas from the compressor or by spraying warm water over the cans. This ensures that the ice blocks can be easily and safely extracted without damaging the cans or affecting the next cycle. The defrost system also helps maintain the efficiency of the plant by reducing downtime between batches.

COMPONENTS	SPECIFICATIONS
Frame and Structure	60cm×50cm×100cm
Compressor	Make: Emerson Climate Technologies; Suction Pressure: 4.8Bar; Discharge Pressure: 19Bar, 2,900rpm
Condenser + Fan	25cm×10cm×20cm Coil OD: 9.52mm, ID: 8.92mm; Material:- Copper; Air Velocity: 900cfm; Tube Length: 3800mm
Expansion Valve	Thermostatic Expansion Valve (TEV)
Evaporator (Tank with Insulating Material)	Dimensions: 20cm×20cm×21cm; Coil OD: 9.52mm, ID: 8.92mm Material:- Copper, Insulating Material: Raw cool; Tube Length: 15000mm

Table 1. Specification for different components

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II. LITERATURE SURVEY

J.P. Yadav [1] in their analysis and fabrication work on an ice plant model, offered basic comprehension of the total system design and performance criteria. Their research proved valuable in identifying how the principal components interact at the plant level. Theoretical (COP) = 5.092

H. S. Salave [2] concentrated on design optimization of a test rig for an ice plant so that it would be applicable to both commercial and laboratory applications. He calculated: Theoretical (COP) = 2.95, R.E = 1752KJ, Actual (COP) = 1.22

Khaing Zar Nyunt [3] highlighted COP calculation and demonstrated the environmental and efficiency advantages of a transition from R134a to R32 refrigerant. Theoretical (COP) = 2.97, Actual (COP) = 1.29

Nahian Masud [4] designed a small air-cooled refrigerant condenser. They outlined an extensive design procedure for the condenser, which is a useful guide to create effective space-constrained heat exchange systems.

Juned Shaikh [5] constructed a prototype test rig for an ice plant intended to compare system COP and minimize refrigeration time. They used R134a as the major refrigerant and brine as the secondary medium in their design, providing a useful way to study system performance and experimental testing.

Munawar Nawab Karimi [6] The research incorporates the work done by different authors on the optimization of condensers and bringing about necessary modifications to reduce the power consumption and also to give better efficiency.

Tikaram Verma [7] For the design purpose cooling load required to produce definite quantity of ice estimated using heat transfer relation is calculated by using vapor compression cycle.

N. C. Nwasuka [8] This research looked at the evaluation and design of a condenser using R134a refrigerant by varying different parameters together. Previous literatures compared the behaviors of different condensers when subjected to R22, R407a etc.

Objectives

- Optimum Design of ice plant test rig.
- Analyzing Performance Parameters using suitable software.

III. RESEARCH METHODOLOGY

Numerical Analysis:

Input Data

Initial temperature of water = 27 ℃ Final temperature of water = 0 ℃ Final temperature of ice = -10 ℃ Initial temperature of brine = 27 ℃ Final temperature of brine = -10 ℃ Mass of water = 1kg

Cp of water = 4.187 KJ/Kg

Heat removal from water $Q_w = m*C_p*\Delta T$

Cooling load

$Q_{cond} = Q_{evap} + W_{compressor}$ Q_{cond}=0.513kw Condenser calculation: -

Overall heat transfer coefficient $U = 1/u = 1/h_r + t/k + 1/h_a$

$$LMTD = \frac{\Delta T1 - \Delta T2}{\ln(\frac{\Delta T}{\Delta T2})}$$

Area of condenser $Q = A \times U \times \Delta T_{lm}$ $A = 2.31 m^2$

Tube length

$A = \pi * D_o * L * N$ L=3860mm

Evaporator calculation: - Overall heat transfer coefficient $U = 1/u = 1/h_r + R_{wall} + 1/h_a$

Area of evaporator

$$LMTD = \frac{\Delta T1 - \Delta T2}{\ln(\frac{\Delta T1}{\Delta T2})}$$

$A = Q/u^* \Delta T_{lm}$ $A = 0.462 m^2$

Tube length

$A = \pi^* Do^* L^* N$ L=15044mm

No.	Description	Symbol	Result	Unit
1	Amount of heat rejected by condenser coil	Qcond	0.399	kW
2	Mass flow rate of air	m	0.0696	kg/s
3	Outside diameter of condenser coil	Do	9.52	mm
4	Reynolds Number	Re	353.5	-
5	Overall Heat transfer coefficient	U	25.087	W/m^2K
6	Area	Ao	2.31	m^2
7	Length of condenser coil	L	3.86	m

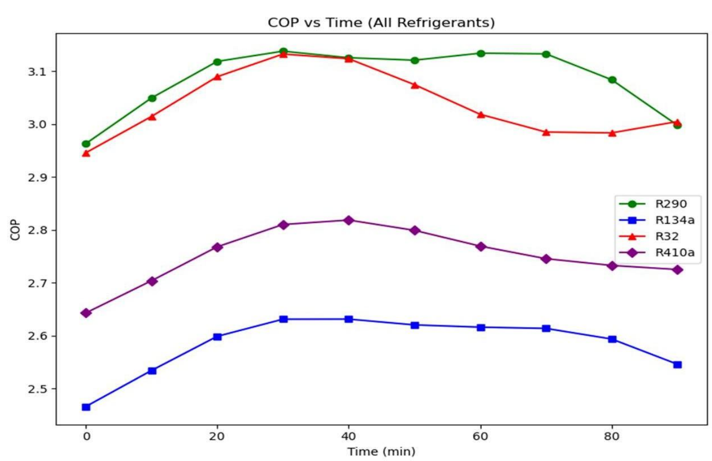
Table 2. Design Result Data for Ice Manufacturing Plant (Condenser)

No.	Description	Symbol	Result	Unit
1	Cooling load	Qw	0.399	kW
2	Overall Heat transfer coefficient	U	36.08	W/m^2K
3	Area	Ao	0.462	m^2
4	Length of evaporator coil	L	1.54	m

Table 3. Design Result Data for Ice Manufacturing Plant (Evaporator)

IV. RESULT AND DISCUSSION

COP Vs Time



- **R290 (Green Line)** consistently delivers the highest COP across the entire duration, indicating superior energy efficiency compared to the other refrigerants. It peaks around 30–50 minutes and remains relatively stable thereafter.
- **R32 (Red Line)** shows performance close to R290, with a slight drop after 40 minutes, but overall remains the second- best in terms of COP values.
- **R410a (Purple Line)** maintains moderate COP values throughout, outperforming R134a but not matching R32 or R290.

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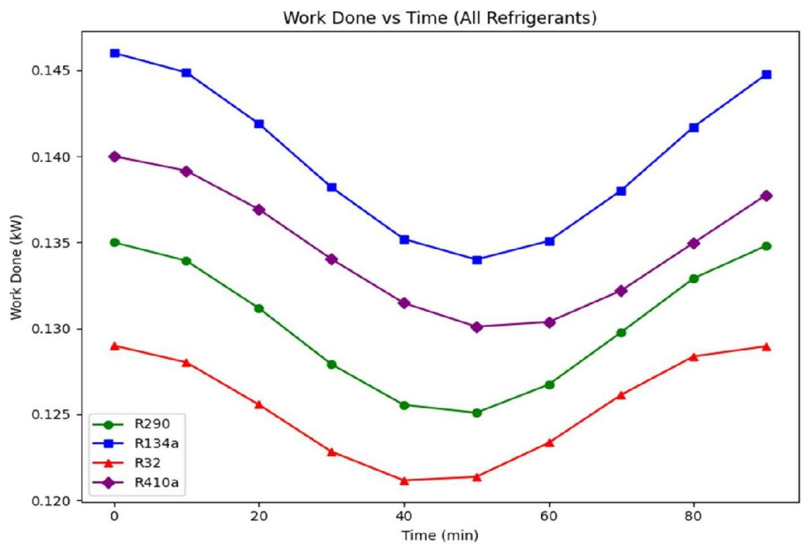
- **R134a (Blue Line)** has the lowest COP consistently, indicating it is the least energy efficient among the refrigerants tested.
- **R32 exhibits a high Coefficient of Performance (COP), closely following R290 throughout the operational duration.** Its COP remains consistently above 3.0 for most of the cycle, indicating **strong thermal performance and excellent energy efficiency**.

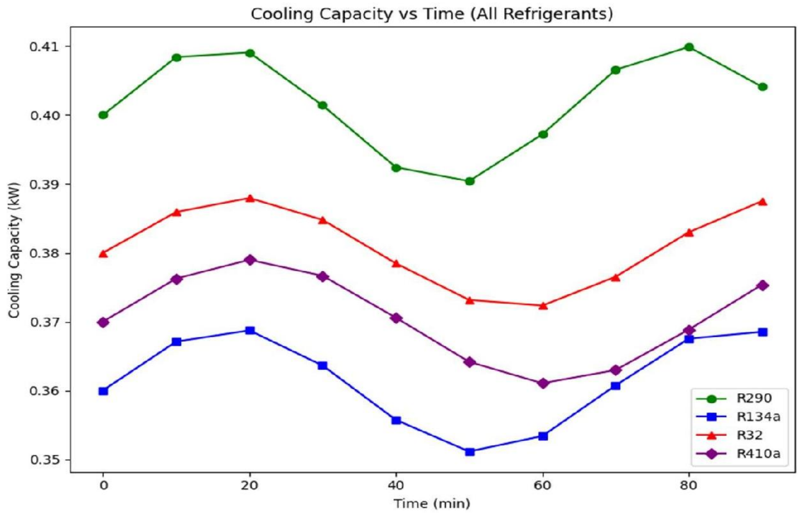
Work done Vs Time



- **R32 (Red Line)** consistently requires the **least amount of work**, especially from 20 to 60 minutes. This indicates
- **higher thermodynamic efficiency**, as less energy input is needed to achieve the desired cooling effect.
- **R290 (Green Line)** shows slightly higher work done than R32 but still remains more efficient than R410a and R134a.
- **R410a (Purple Line)** requires moderate work input, with a trend higher than R32 and R290 but lower than R134a.
- **R134a (Blue Line)** requires the **most work throughout the cycle**, indicating **lowest energy efficiency** among the tested refrigerants.

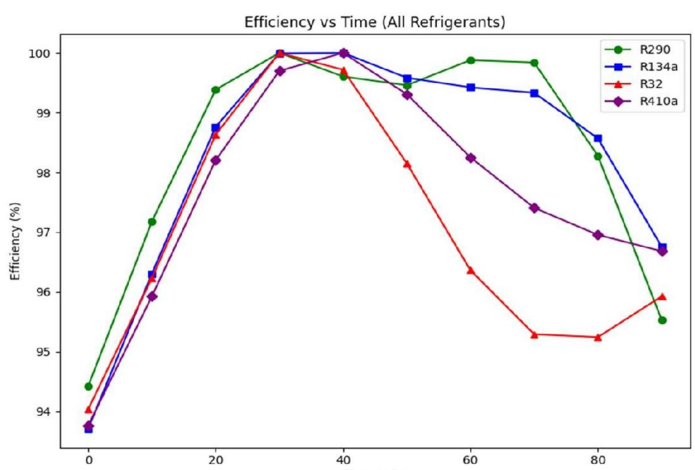
Among all refrigerants, **R32 demonstrates the lowest work input requirement**, making it the **most energy-efficient choice in terms of work done**. This not only reflects better performance but also implies **lower operational costs and reduced energy consumption**.

Cooling capacity Vs Time



- R32 (Red Line) shows the lowest work input throughout the entire time span, dropping as low as ~0.121 kW around the 40-minute mark. This indicates superior energy efficiency, making R32 the most efficient refrigerant in terms of power consumption.
- R290 (Green Line) ranks second in terms of efficiency, requiring slightly more work than R32 but still significantly lower than R410a and R134a.
- R410a (Purple Line) exhibits moderate work requirements, placing it in the mid-range efficiency category.
- R134a (Blue Line) consistently records the highest work input (above 0.145 kW initially and at the end), indicating poorer energy performance compared to the other refrigerants.
- R32 is the best-performing refrigerant in terms of energy efficiency, as it consistently requires the least amount of work to operate the system. This results in lower power consumption, reduced operational costs, and improved sustainability.

Efficiency Vs Time



- **R290 (Green Line)** shows the most **consistent high efficiency**, reaching near 100% around 30–40 minutes and maintaining it for a longer duration with only a slight drop toward the end.
- **R134a (Blue Line)** also reaches close to 100% efficiency by 40 minutes and maintains above 99% for much of the cycle, with a moderate drop after 70 minutes.
- **R32 (Red Line)** reaches peak efficiency around 30–40 minutes but shows a **more noticeable decline after 50 minutes**, dropping to about **95% efficiency** near the end. However, it still performs reasonably well in the early to mid-phase.
- **R410a (Purple Line)** follows a similar trend as R32, with good performance early on but gradually declining toward the end.
- **R32 demonstrates excellent efficiency in the early to mid stages of operation**, reaching up to **100% efficiency around 30–40 minutes**, which highlights its capability to deliver **maximum performance during peak operation periods**

Selection of R32 refrigerant:

R32 is an ideal refrigerant for this project due to its high energy efficiency, achieving a Coefficient of Performance (COP) above 3.0, which reduces power consumption while maintaining excellent cooling output. It requires minimal work input (~0.121 kW), particularly during peak operation, ensuring lower operational costs. R32 also performs at 100% efficiency during critical periods, offering optimal performance when cooling demand is highest. With a lower Global Warming Potential (GWP) than R134a and R410a, it's a more environmentally friendly choice. Proven in HVAC and refrigeration systems, R32's reliability and compatibility make it a sound, sustainable, and cost-effective option.

V. CONCLUSION

This research successfully demonstrates the design, development, and performance evaluation of an Ice Plant Test Rig employing R32 refrigerant within a vapor compression refrigeration cycle. The system was designed with a cooling capacity of 0.25 TR and incorporated a hermetically sealed compressor, air-cooled condenser, capillary expansion device, and a shell-and-tube evaporator immersed in a brine solution to ensure effective heat exchange.

The choice of R32, motivated by its favorable thermodynamic properties and lower Global Warming Potential, contributed to improved system efficiency while aligning with current environmental standards. Experimental results indicated that the rig performed reliably under the designed conditions, with the measured Coefficient of Performance (COP) closely matching theoretical expectations. The temperature distribution and system stability further validate the efficacy of the design.

In conclusion, the developed test rig offers a cost-effective, efficient, and environmentally sustainable solution for small- scale ice production. It also serves as a valuable experimental platform for academic and research-oriented applications focused on refrigeration and thermal systems.

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